EUV Conversion Efficiency of Tin-Based Laser Plasma Sources

Majid Masnavi, Martin Richardson, Homaira Parchamy, John Szilagyi, Nathan Bodnar, and Joshua D. Bradford

The Townes Laser Institute, The College of Optics and Photonics, University of Central Florida, USA

P-SO-07
Oct 27-29, 2014. Washington DC

1. High power mass-limited Sn EUV source

High brightness, laser-based, EUV plasma lamps at 13.5 nm are one of the essential components of EUV lithography steppers for manufacturing the next generation of microelectronics [1-9]. Plasma sources providing power of > 200 W of inband power at the intermediate focus are required now for current stepper systems, with the expectation that powers as high as 1 kW will be required in the future. As a consequence, the highest possible conversion efficiency (CE) of laser plasma sources is demanded to reduce laser costs and footprint. This study examines the optimum regions of laser-plasma operational space for obtaining high CE's for a number of laser-irradiated mass-limited tin droplet source scenarios. It is made through the use of 1D and 2D hydrodynamic plasma modeling coupled with a population kinetics code. The population kinetics solver includes all of the transitions associated with the most important excited-state configurations in the Sn I-Sn XXII charge states, using detailed atomic data obtained from HULLAC and FAC codes including the effects of configuration interaction.

2. UCF has been developing tin-doped micro-droplet EUVL source driven by solid-state lasers for several years
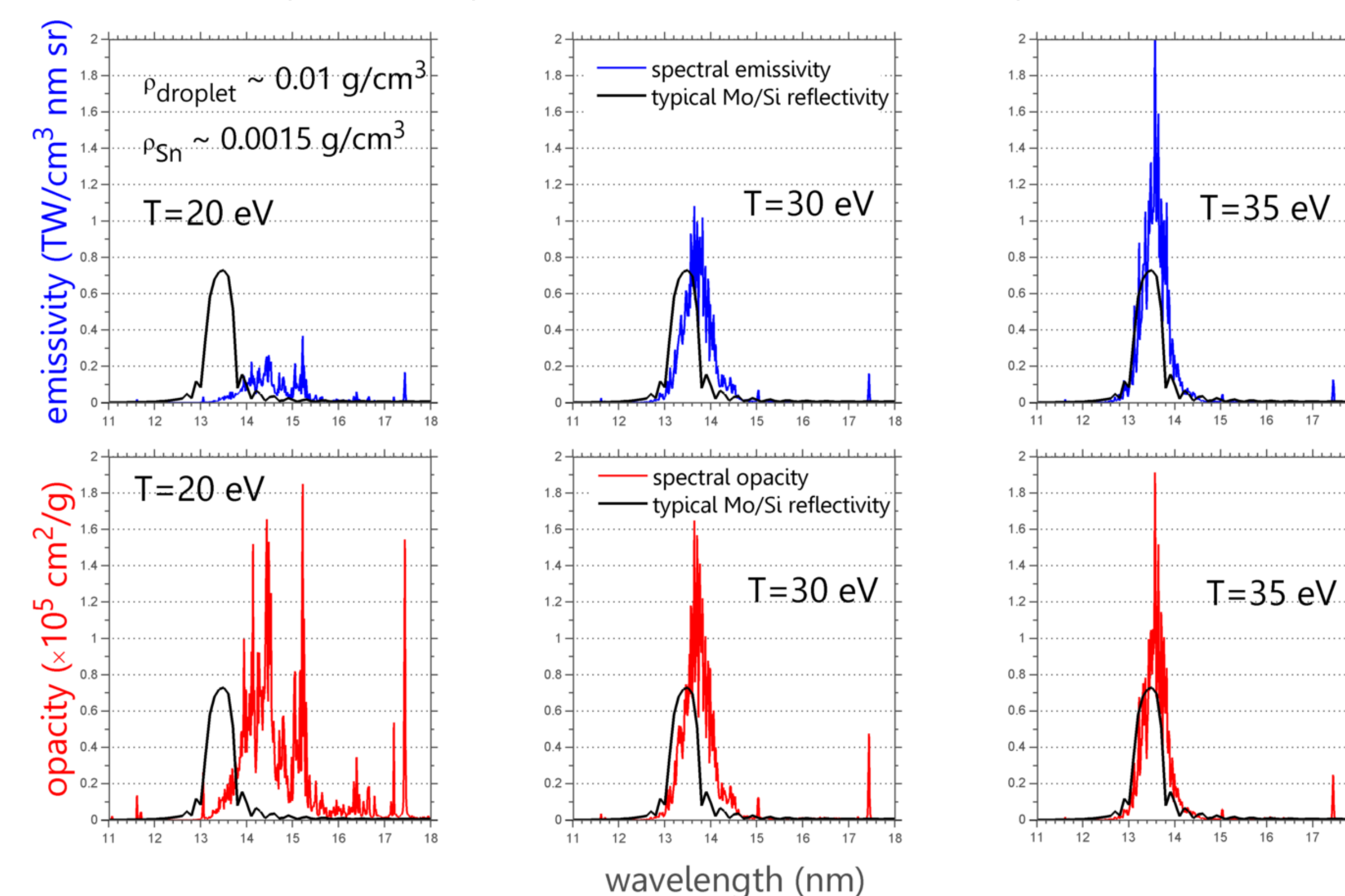
M. C. Richardson et al., 4th International EUVL Symposium, Lake Tahoe, CA, November (2005).

30 kHz source
35 μm

Droplet velocity 30 m/s
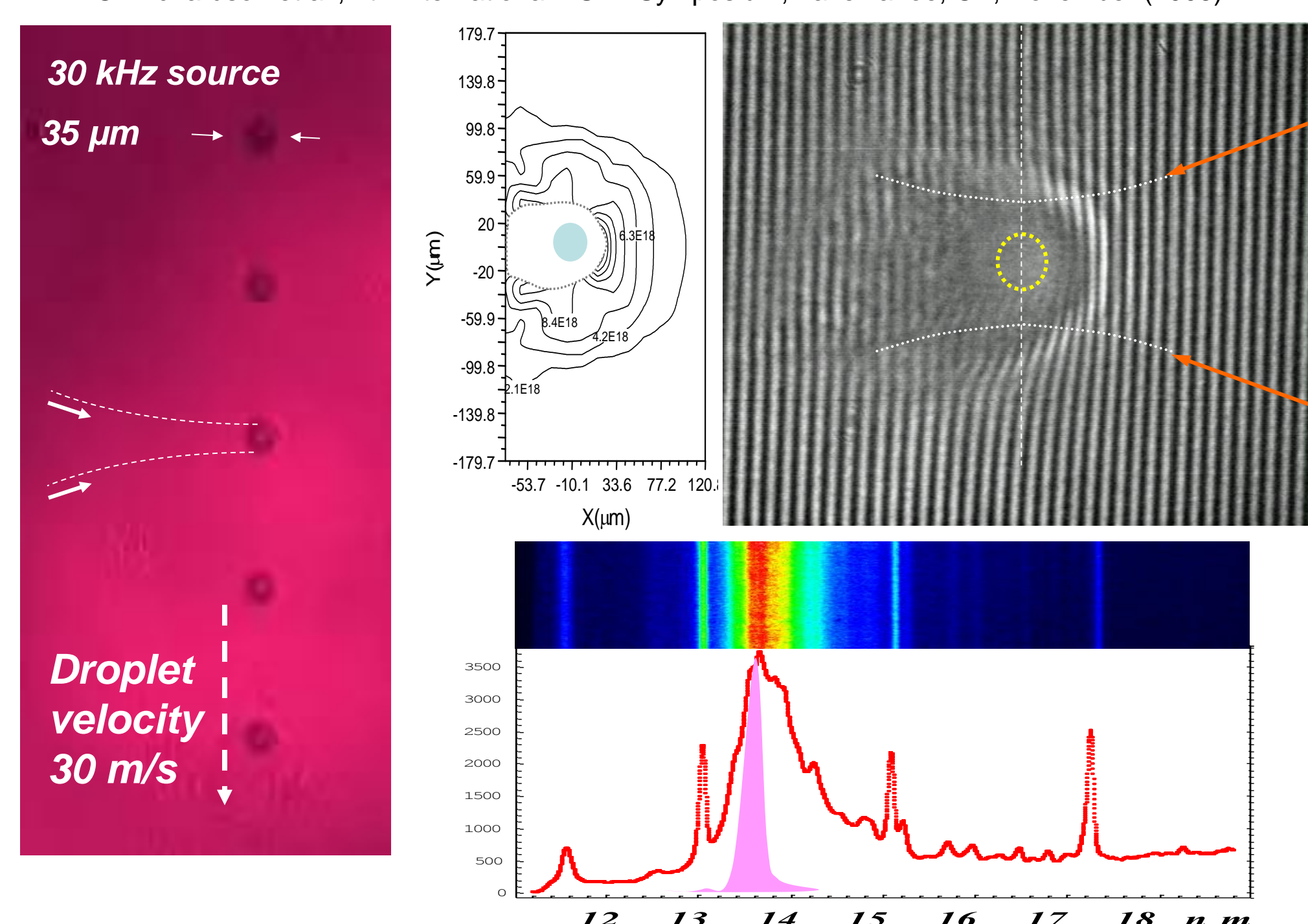
Room temperature doped tin liquid micro-droplet contains > 1% Sn of solid tin droplet.

## 3. UCF has been developing a non-LTE population kinetics code for tin-doped droplet

Constructed atomic database on the density-temperature-concentration grid using detailed level accounting approach.

$\rho_{droplet} \sim 0.01$ g/cm^3
$\rho_{Sn} \sim 0.0015$ g/cm^3

T=20 eV · T=30 eV · T=35 eV

spectral emissivity
typical Mo/Si reflectivity

spectral opacity
typical Mo/Si reflectivity

T~ 35 eV results in strong inband emission of the doped Sn droplet.

5. Spectral efficiency of pure Sn and doped Sn droplet

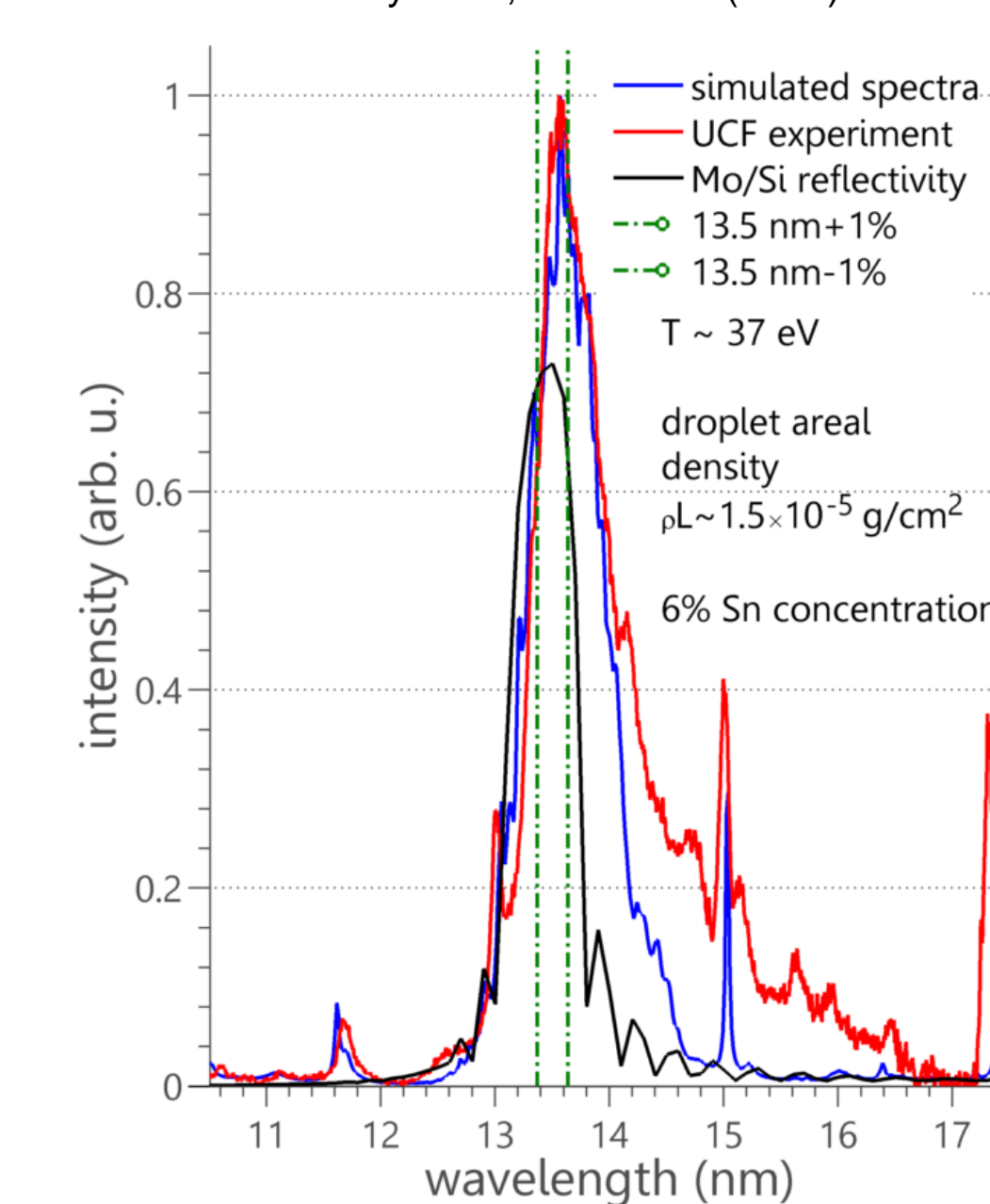The optimum regime of the spectral efficiency shifts to higher density region in the Sn doped droplet.

100% Sn · 13% Sn · 10% Sn
6.5% Sn · 3% Sn · 1% Sn

droplet diameter = 40 μm
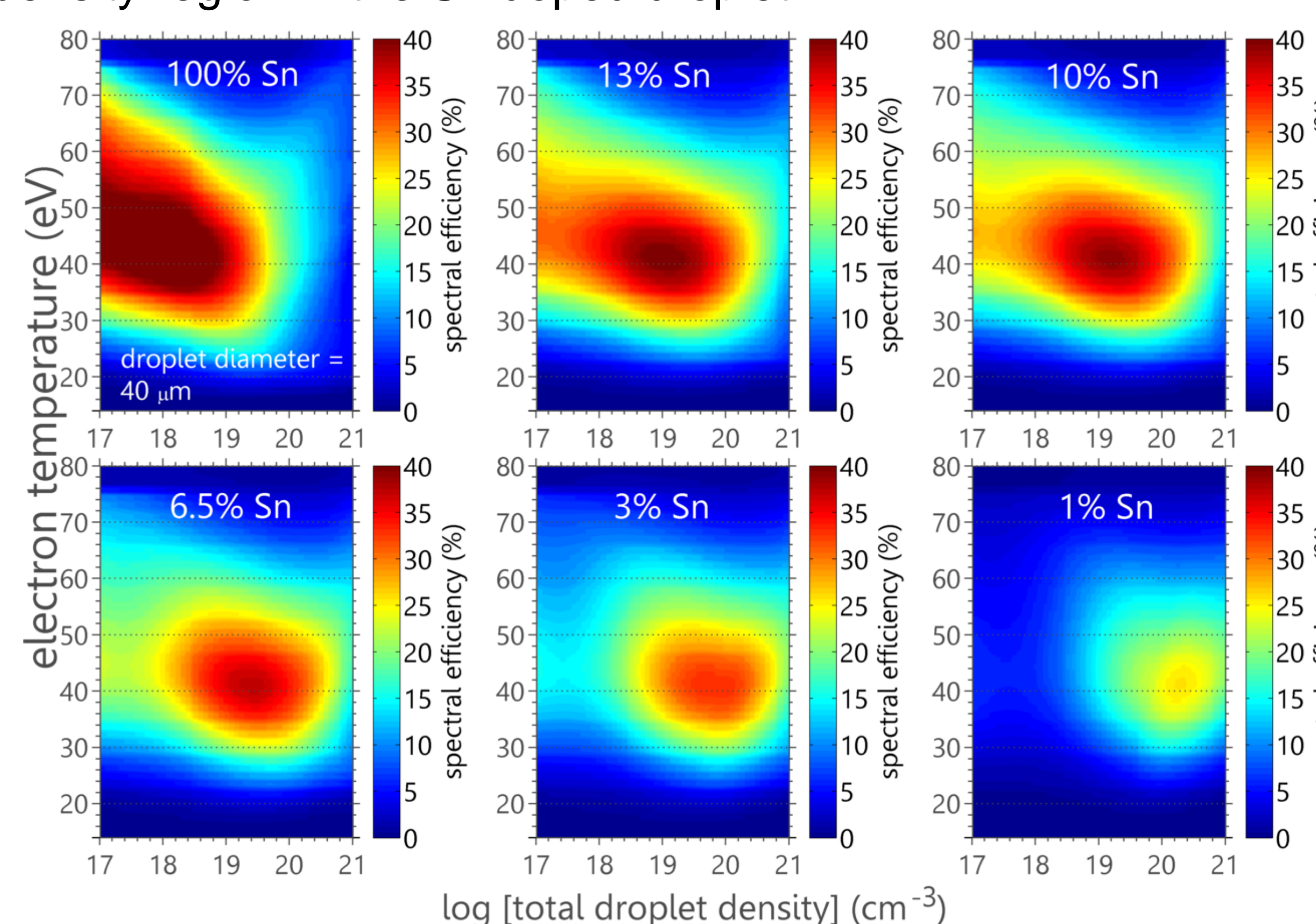
4. Comparison of simulated spectra & mass-limited Sn droplet in UCF experiment

Simulated spectra for a homogenous plasma reproduces inband experimental features [1-4].
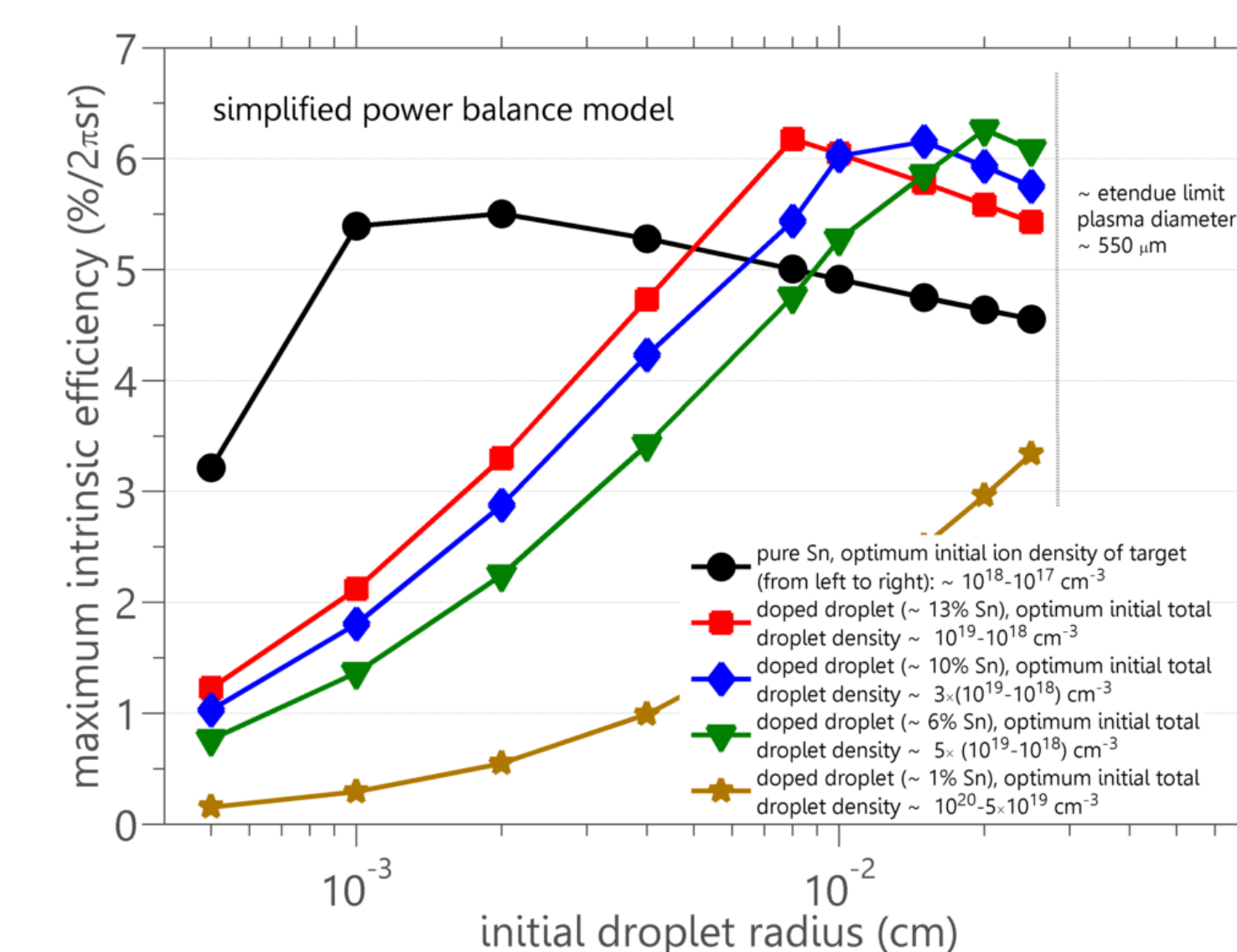
C. S. Koay *et al.*, Proc SPIE (2005) 5751.

simulated spectra
UCF experiment
Mo/Si reflectivity
13.5 nm+1%
13.5 nm-1%

T ~ 37 eV

droplet areal density
$\rho_L \sim 1.5 \times 10^{-5}$ g/cm^2

6% Sn concentration

We predicted CE for the inband region of 13.5±0.135 nm.

6. Power balance: maximum intrinsic CE of pure Sn and doped Sn droplet

Maximum intrinsic CE predicted using the non-LTE population kinetics model.

simplified power balance model

etendue limit plasma diameter ~ 550 μm

- pure Sn, optimum initial ion density of target (from left to right) ~ 10^{18}-10^{17} cm^{-3}
- doped droplet ~ 13% Sn), optimum initial total droplet density ~ 10^{18}-10^{18} cm^{-3}
- doped droplet (~ 10% Sn), optimum initial total droplet density ~ 3-10^{18}-10^{18} cm^{-3}
- doped droplet (~ 6% Sn), optimum initial total droplet density ~ 5-10^{18}-10^{19} cm^{-3}
- doped droplet (~ 3% Sn), optimum initial total droplet density ~ 5-10^{18}-10^{19} cm^{-3}
- doped droplet (~ 1% Sn), optimum initial total droplet density ~ 10$^{19.5}$-5-10^{19} cm^{-3}
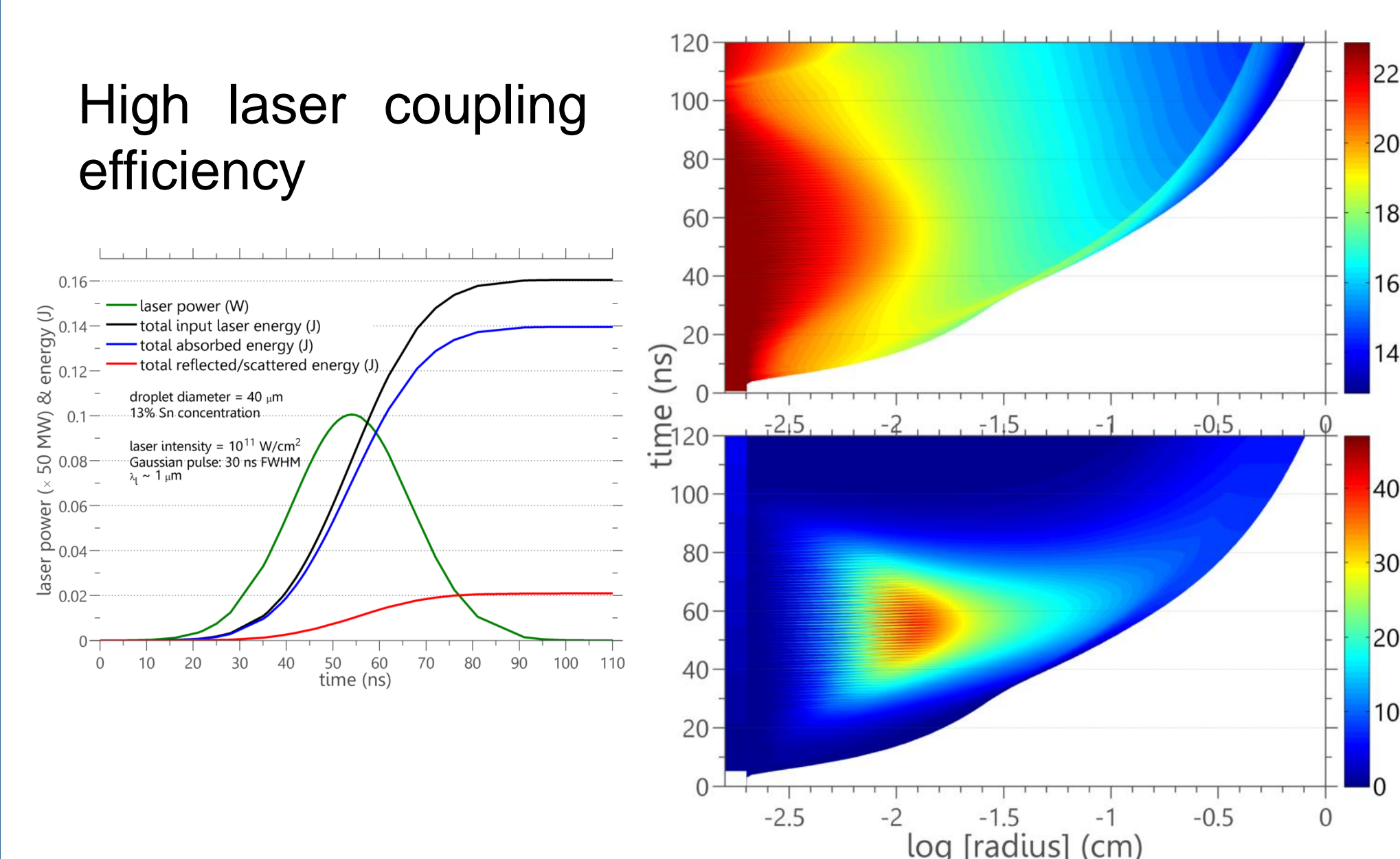
Maximum intrinsic CE occurs at the average inband optical depth, (photon mean free path) ~ 1.

7. 1D radiation-hydrodynamics simulation of mass-limited Sn droplet

Typical 1D simulation for doped Sn droplet: effective parameters for density, atomic weight, and atomic number were used.

High laser coupling efficiency

laser power (W)
total input laser energy (J)
total absorbed energy (J)
total reflected/scattered energy (J)

droplet diameter = 40 μm
13% Sn concentration

laser intensity = 10^{11} W/cm^2
Gaussian pulse: 30 ns FWHM
τ = 1 μm

Total emission is collectable, the plasma diameter < 500 μm, see, contour of electron temperature and streak.

10^{11} W/cm^2
30 ns FWHM

doped Sn droplet
40 μm diameter
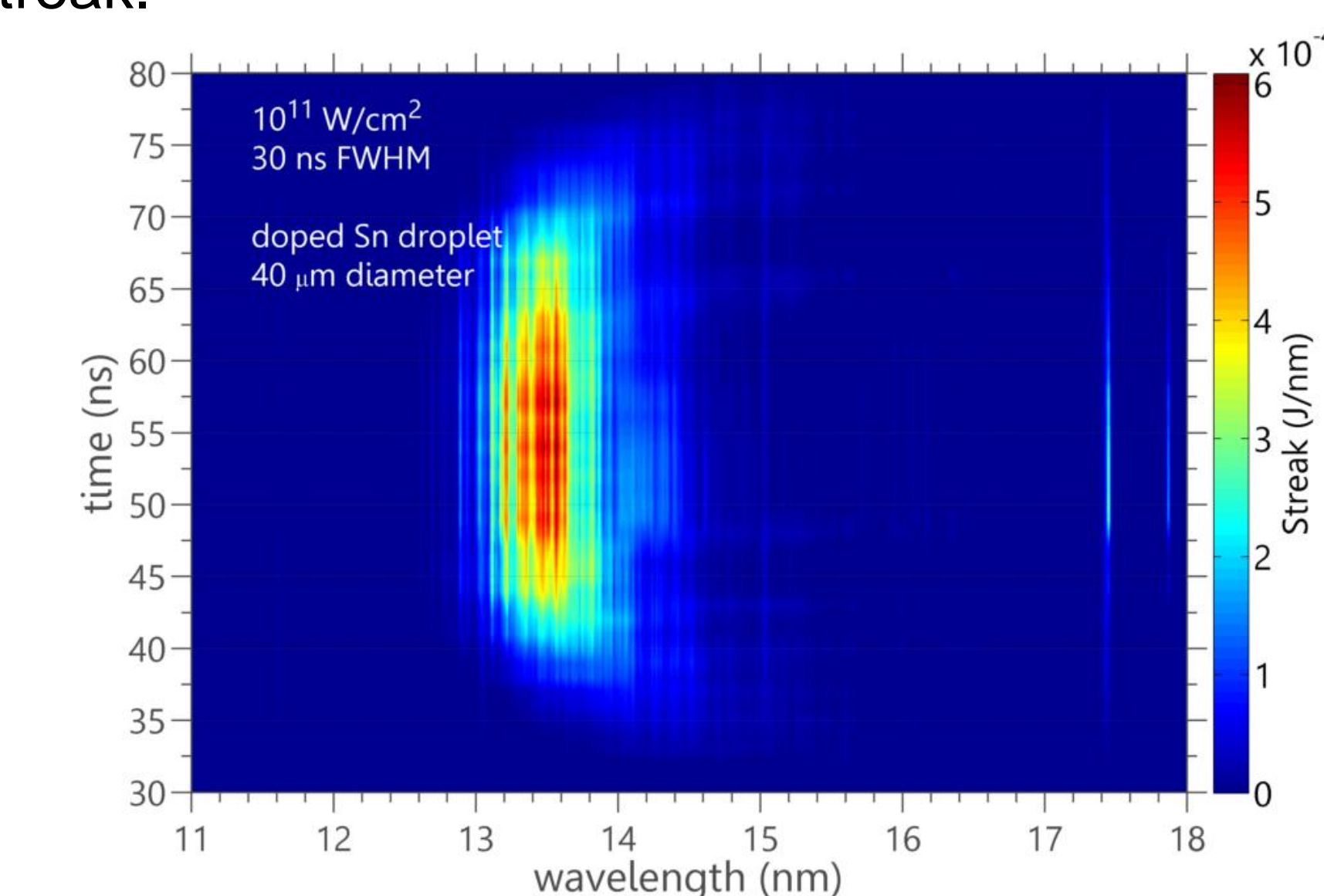
References

[1] M. C. Richardson *et al.*, In EUV Sources for Lithography, edited. by V. Bakshi (SPIE, Bellingham, WA, 2005).
[2] S. Ellwi *et al.*, 1st International EUVL Symposium, Dallas, Texas, October (2002).
[3] M. C. Richardson *et al.*, 4th International EUVL Symposium, Lake Tahoe, CA, November (2005).
[4] M. C. Richardson *et al.*, Chapter in book "EUV lithography", edited by Banqi Wu (2008).
[5] B. A. M. Hansson *et al.*, In the Proceedings of SPIE, 6151 (2006) 61510R.
[6] Al-Rabban et al., In EUV Sources for Lithography, edited. by V. Bakshi (SPIE, Bellingham, WA, 2005).
[7] C. S. Koay *et al.*, Proc SPIE (2005) 5751.
[8] M. Masnavi *et al.*, J. Appl. Phys. 101 (2007) 033306.
[9] M. Masnavi *et al.*, Appl. Phys. Lett. 102 (2013) 164102.